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36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit (Statement A)
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AIAA 2000-3679

Testing of an Advanced Liquid Hydrogen Turbopump

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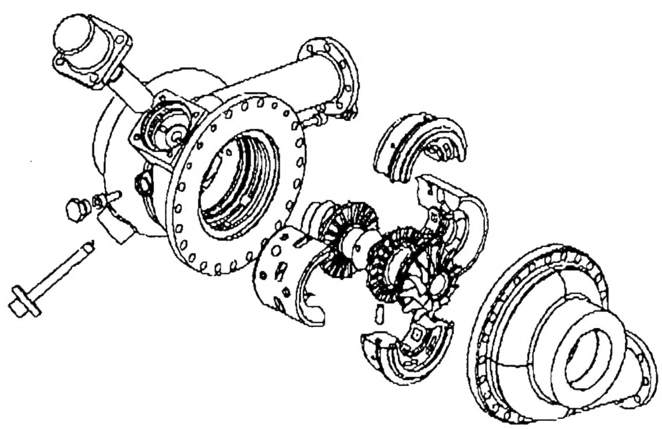

36th AIAA/ASME/SAE/ASEE Joint Propulsion
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Huntsville, Alabama

ABSTRACT

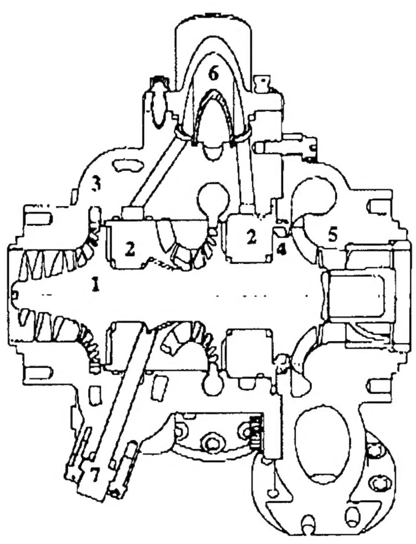
This paper discusses the testing of an Advanced Liquid Hydrogen Turbopump for a 50,000 pound (222.4 kN) thrust Upper Stage Expander Cycle Engine being developed by Pratt & Whitney Liquid Space Propulsion under contract to the United States Air Force Research Laboratory (AFRL) to support the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program. The ~~Advanced Liquid~~ Hydrogen (ALH) Turbopump is designed to provide improved system thrust to weight, decreased hardware/support costs, and increased reliability. These benefits will be demonstrated through test of this high speed, high efficiency, two stage hydrogen turbopump.

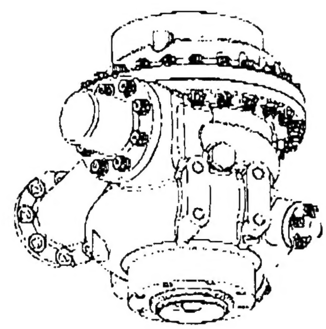
INTRODUCTION

The Air Force, Army, Navy and NASA have implemented a three phase, 15-year rocket propulsion technology improvement effort to "double rocket propulsion technology by the year 2010". This program, designated the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) initiative has established performance, reliability and cost improvement goals for each of the three phases. These goals are to be achieved by advancing component technology through design, development and finally demonstration. Pratt & Whitney (P&W) Liquid Space Propulsion (LSP) under contract to the United States Air Force Research Laboratory (AFRL, contract F04611-97-C-0029) is testing an Advanced Liquid Hydrogen (ALH) turbopump designed and manufactured under a separate AFRL contract (F04611-94-C-0008). This turbopump is designed to support the IHPRPT H2/O2 boost/orbit transfer propulsion area Phase I goals. These system level goals include: a 1% improvement in vacuum specific impulse, a 30% improvement in thrust to weight, a 15% reduction in hardware manufacturing and support costs and a 25% improvement in reliability relative to current state-of-the-art levels.

To achieve the IHPRPT Phase I engine goals the ALH turbopump design, shown in Figure 1, uses a fluid film rotor support system. The fluid film bearings free the pump design of the constraints associated with conventional rolling element bearings, allowing high rotor speeds, which also permits a reduction in pump size and weight. At full power operation, the ALH is expected to produce an overall pump pressure rise of 4,500 psid (306 kg/cm^2) at a 16 lbm/sec (7.3 kg/sec) flowrate.

Testing the ALH has provided considerable knowledge of the new technologies incorporated into the turbopump design. The ALH turbopump has completed tests on 8 builds of the hardware. Since the first test, the ALH team has gained an improved understanding of the ALH start transient characteristics in a component test





Major Features:

1. One piece rotor.
2. Split fluid film bearings.
3. Cast pump housing with integral crossover passages.
4. Radial inflow turbine. — turbines?
5. Cast turbine housing with vaneless inlet volute.
6. Filtered bearing supply.
7. Capacitance proximity probe

Figure 1 – Advanced Liquid Hydrogen Turbopump

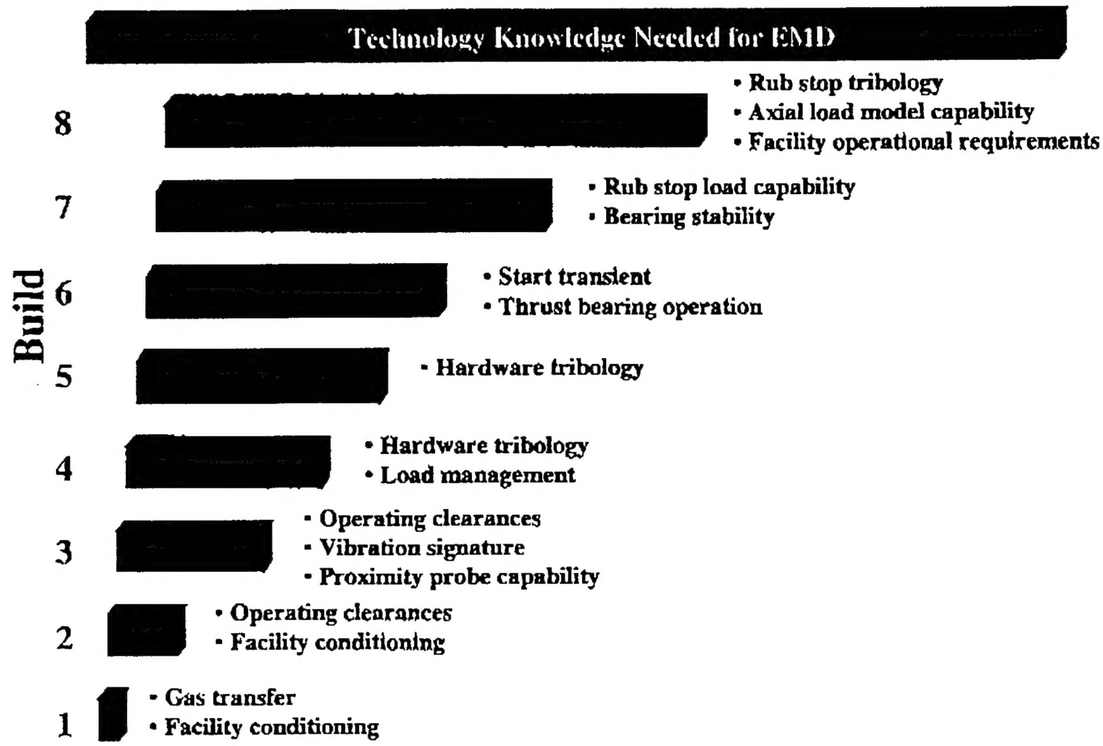


Figure 2. Technology Enabling Knowledge Gain from ALH Testing

environment. Figure 2 shows the key knowledge gained from testing the ALH and compares the progress to the total knowledge needed to initiate an Engineering and Manufacturing Development (EMD) program. Each build has provided improved comprehension of the enabling technology fundamentals: thermal modeling and critical clearances in a liquid hydrogen environment, component testing considerations, rotor structural response during different phases of operation, axial loads and power absorption, turbine aerodynamics, hardware tribology, the capabilities of the capacitance proximity probe, and the primary technology - fluid film bearing performance.

DISCUSSION

Thermal Modeling and Critical Clearances

The performance objectives of the ALH require tightly controlled operating clearances at cryogenic conditions. Early ALH test results indicated axial clearances were not as expected and wear patterns observed on the diametrical surfaces of the bearings suggested clearance issues there also. Initial interference problems were traced to a dimensional non-conformance in the non-critical areas of the rotor, which was corrected following build two of the turbopump. Hardware distress observed following build two testing continued to show indications on the bearing surfaces, turbine and impeller blades. To calibrate the hardware thermal model cryogenic immersion testing was performed, first in liquid hydrogen, then using liquid helium. Using special marking compounds areas of potential interference were investigated. Axial travel was also verified during the immersion tests. Several parts were also dimensionally inspected at cryogenic temperatures to obtain further information regarding the thermal contraction properties of the hardware. This data validated the thermal model of the rotor and provided information on potential improvement opportunities for the pump and turbine housing models. The tests also confirmed that the distress patterns observed on the bearings were not the result of thermally induced interferences.

Component Testing

Component level testing of the ALH turbopump has consisted of some eight different build configurations and a total of 18 tests. Throughout the test program, four (4) important test philosophies have surfaced which have guided the success of this program: 1) rotordynamic concerns, 2) axial load control, 3) maximizing turbine torque, and 4) wear tolerance.

Rotordynamic Concerns:
The primary rotordynamic operability concerns were certain blade modes and critical speeds. To ensure potential rotordynamic instabilities were avoided, test profiles were scheduled to operate the turbopump only at the steady-state conditions expected during engine operation where the engine would start to 60% Rated Power Level (RPL) and then ramp to 100% RPL. Aside from the first and second builds of the ALH, which targeted a conservative 35% RPL to validate pump operation at that power level, all subsequent tests have focused on achieving the 60% and 100% RPL points.

Axial Load Control:
Early on in the test program, it was determined that axial loads would play an important roll in understanding how best to operate the turbopump through transients (start/shutdown) as well as at steady state. An axial load imbalance at steady state could prove catastrophic due in part to the lack of axial surfaces capable of withstanding the energy one might encounter during pump operation. Extensive work went in to the understanding of axial loads and their impact on starting the ALH turbopump. Data obtained from each test was used to improve the calibration of the axial load model. The model was used to verify load conditions throughout the test.

Maximizing Turbine Torque:
The ability to generate maximum turbine drive torque without causing excessive gas transfer into the pump bearings proved to be an important lesson that was also learned during testing. Maximum turbine torque is provided by ensuring the proper thermal environment of the turbine is maintained and allowing for maximum pressure ratio (via venting the turbine discharge to ambient) during the initial spin-up of the rotor.

Wear Tolerance:
Teardown results of the various builds showed evidence of wear data that provided insight into the durability of various ALH turbopump rub surfaces. The complexities involved in rotor/stator repair techniques as well as the wear data itself required incorporation of a supplemental rub surface for transient operation.

Successful testing of the ALH turbopump has been achieved by incorporating the four philosophies into the test procedures. Experience has shown us that each plays an important role in the understanding of what it takes to successfully run the ALH turbopump. These philosophies equally important in deciding the outcome of an ALH test.

Structural Response

Capturing and evaluating high-speed dynamic events with accelerometers and displacement probes to understand the motion of the rotor throughout a given test has been the primary focus for structural dynamic assessment. Although data interpretation continues to pose challenges in this area, a couple of dynamic response observations have been identified to aid the development process. Of the many data observations, two major rotor motion areas have dominated:

Harmonic Response:
After an initial shock caused by axial rotor to housing contact, harmonics (Figure 3) were observed at relatively high frequencies. Harmonic content has been detected beyond the 10^{th} order with varying levels of amplitude.

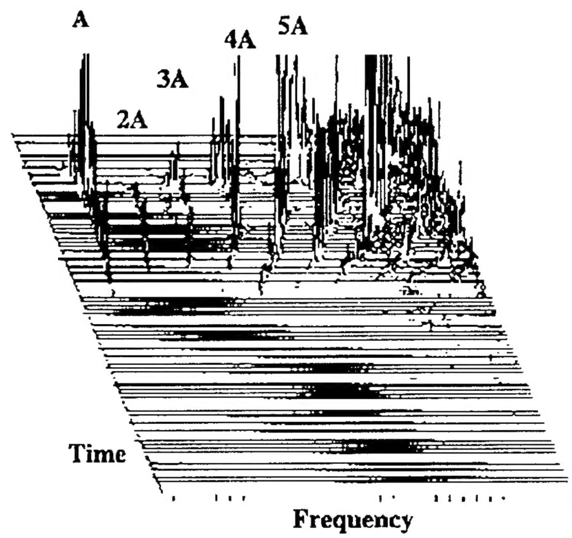


Figure 3 - Harmonic Response

Random Response:
White noise random vibration has been observed during periods of operation. Figure 4 shows this response at two separate periods during a test.

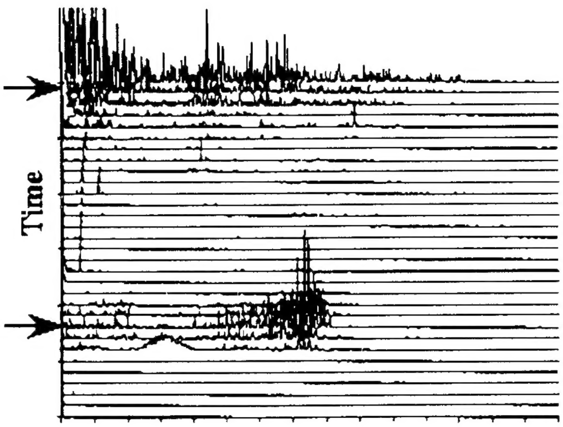


Figure 4 - Random Noise

Sequencing these dynamic events for a given test has lead to a useful understanding of rotor motion and facilitated corrective actions for the hardware.

Thrust Balance and Power Absorption

The ALH turbopump design goals of maximizing pump discharge pressure while minimizing turbopump weight and production costs (size and parts count) resulted in a design that required maximizing rotor speed while minimizing impeller diameter. Accurate axial and radial forces predictions are critical to preventing contact surface degradation and achieving test requirements (start to power, steady-state RPM and performance).

A transient/steady-state thrust balance/power absorption model was developed prior to testing that was incorporated into the ALH/facility simulation model so that an ALH test run program (facility requirements for testing) could be developed. The model's pump section (1^{st} and 2^{nd} impeller) was based on RL10 experience. The model's turbine section was based on a radial in-flow turbine meanline analysis. The hydrostatic thrust bearing axial loading is towards the turbine and is designed to offset the pump and turbine loads during operation. The thrust bearing load capability analysis is based on a comprehensive fluid film bearing model.

The model was improved and calibrated during testing based on turbopump post-test teardown observations and added instrumentation. Post test hardware inspections identified both axial and radial load imbalances that could be correlated to both the corresponding proximity probe data, rotordynamic data and rotor speed changes. Additional accelerometers and proximity sensors, incorporated following build 6 test provided greater detail on the rotordynamic events and rotor position. Supplemental pump side internal pressures sensors were added along the 1^{st} stage impeller blade and backface vane. This data resulted in a better understanding of the 1^{st} stage impeller and backface vane pressure profile. This profile was assumed to hold for the 2^{nd} stage impeller and backface vane as well. Thermocouples were placed in key bearing cavity locations to provide data on fluid conditions. An internal pressure measurement was also added to the outer diameter of the thrust bearing to increase the accuracy of its calculated force and to indicate rotor motion/bearing clearance.

Figure 5 shows the relative start and shutdown axial load imbalance components from the pump, turbine and thrust bearing along with the resultant vector magnitude for the sum of the components. Thrust bearing loads calculations are banded to capture the load variance associated with a bearing operating at the maximum and minimum gaps. A positive value of the resultant axial load indicates the load is towards the turbine, while a negative value indicates the load is towards the pump.

Figure 6 shows a comparison of axial proximity probe data with test data reduction predicted axial thrust balance information. Both proximity probe and axial thrust balance information correlate. When the axial thrust balance prediction indicates that the shaft is moving from one side to the other, the proximity probe data indicates the appropriate motion. This information and the indicated axial rub load from post-test hardware inspections also correlating to the axial thrust balance information shows the fidelity of the axial thrust balance computer model, resulting in improved confidence in future analyses and predictions.

Utilizing the axial load model it is possible to understand the consumption of turbine power by the pump and hardware contact. This understanding leads to modifications in valve schedules to assure hardware contact during the different phases of ALH operation is minimized.

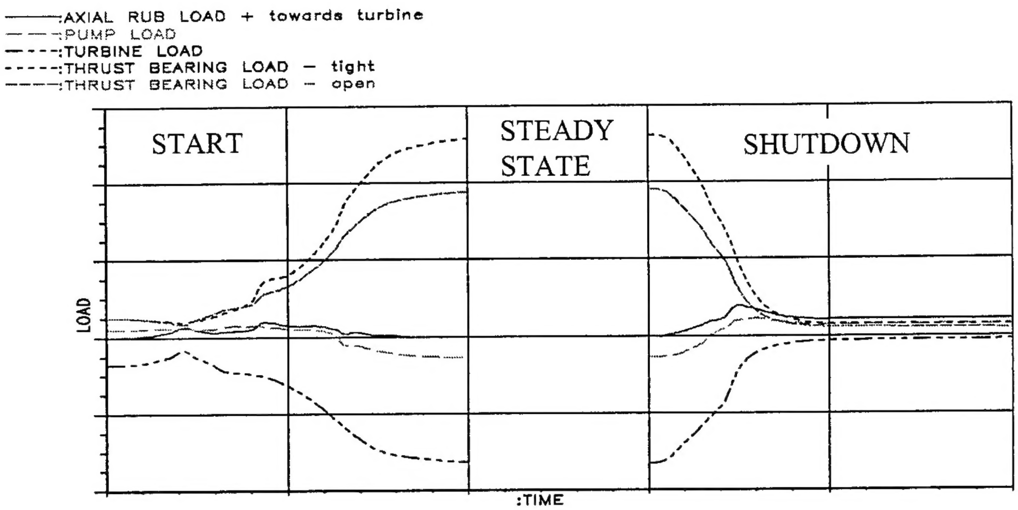


Figure 5 - Net Axial Load Imbalance and Components for Start and Shutdown

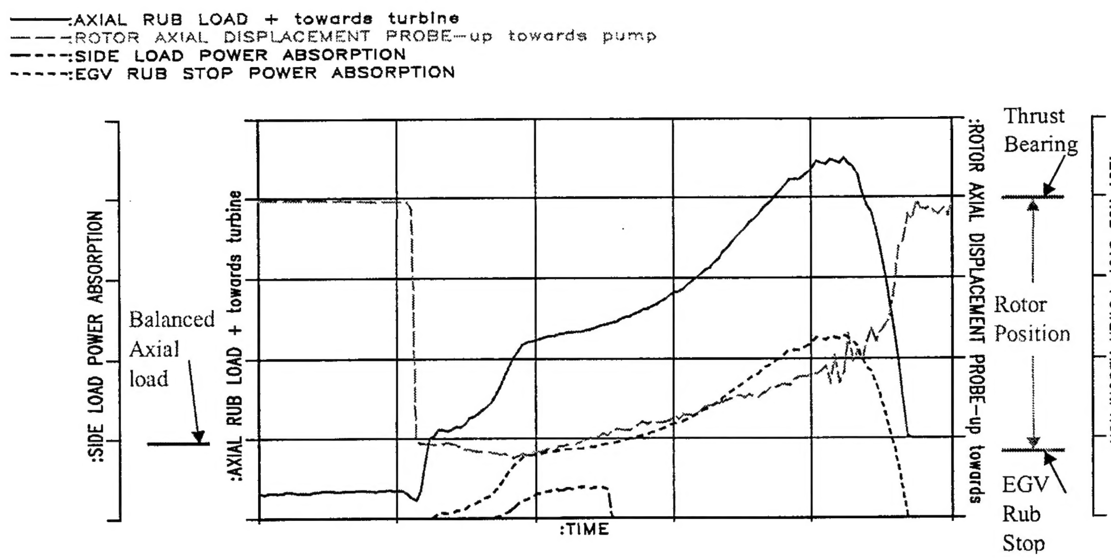


Figure 6 - Power Absorption, Axial Load Imbalance and Rotor Position for Start

Turbine Aerodynamics

The turbine aerodynamics design is described in reference 1; here we present the test results specifically related to the estimation of the transient torque during start up.

The study of the transient torque during start up is based on the unsteady angular momentum equation. In control volume form (Ref. 2) the torque is given by:

Equation 1

$$\vec{T} = \frac{\partial}{\partial t}\int_{CV} \vec{r} \times \vec{V} \rho d\forall + \int_{CS} \vec{r} \times \vec{V} \rho \vec{V} \bullet d\vec{A}$$

Where,

$\vec{T}$ *is the torque*

$\vec{r}$ *is the position vector*

$\vec{V}$ *is the velocity vector*

ρ *is the density*

$\forall$ *is the control volume*

$\vec{A}$ *is the area of the control volume*

CV *is the control volume*

CS *is the control surface*

The first term represents the effects of unsteadiness and the second term, even though affected by the unsteady flow, depends only on the inlet and exit conditions to the turbine and leads to the well known Euler equation for turbomachinery.

The axial contribution from the second term on the right hand side of Equation 1 can be written as:

Equation 2

$$T_z = \dot{m}(r_2 V_{t2} + r_1 V_{t1})$$

where 1 represents the inlet and 2 the exit to the rotor and V_t is the tangential velocity.

To evaluate the unsteady term, we assume that the control volume is fixed as the rotor volume and the changes in tangential velocity with respect to time inside the rotor are mainly due to changes in rotational speed and mass flow.

The first term on the right hand side of Equation 1 can be evaluated as:

$$\frac{\partial}{\partial t}(\bar{\rho}\varpi)\int_{CV} r^2 d\forall + \frac{\partial}{\partial t}\left(\dot{m}\right)\int_{CV}\frac{r\tan\beta}{A}d\forall$$

where we assume that the angle of the flow relative to the rotor, β, is constant with respect to time and the density through the rotor as the average between inlet and exit. The mass flow is $\dot{m}$ and ϖ is the rotational speed. A is the cross sectional area at any point inside the rotor where β is evaluated. After performing the integrals the transient axial torque is given by:

$$T_z = \dot{m}(r_2 V_{t2} + r_1 V_{t1}) + C\frac{\partial}{\partial t}(\bar{\rho}\varpi) + B\frac{\partial}{\partial t}\left(\dot{m}\right)$$

Where C & B are constants.

A plot of the estimated (green) and transient (red) torque in lb.-ft as a function of time in seconds is given in Figure 7.

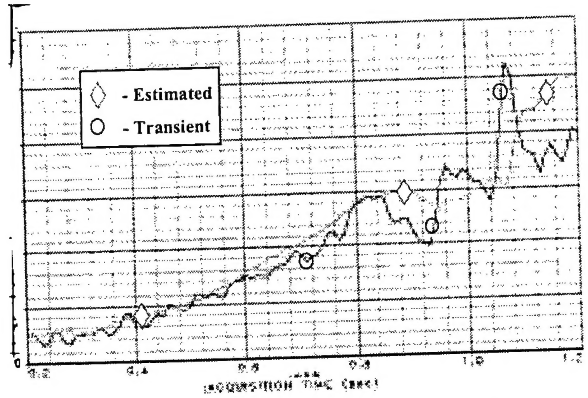


Figure 7 - Estimated (green) and transient (red) torque in lb.-ft as a function of time in seconds

ALH Tribology

With the use of fluid film bearings, a key technology in developing long life, dependable rocket turbopumps, tribology is a critical enabling technology for this design. In contrast to rolling element bearings, the rotor and bearing do not come in contact once normal operation is achieved. The hydrostatic bearing-to-rotor mating surfaces require mechanical properties that will minimize degradation of the two surfaces during transient induced contact periods. Traditionally, one surface will have a fine hard surface with a thin film hard coating finish while the other possesses sacrificial rub coatings. This wear couple is intended to prevent degradation of the surfaces and/or galling associated with conventional bearings. Use of extremely thin film coatings maintains accurate rotor positioning even if the sacrificial stator coating is consumed.

The ALH turbopump rub surfaces initially deployed a material couple that represented a hard-on-hard wear couple. This particular combination allowed for the lowest static friction coefficient and, therefore, minimized starting torque requirements. This wear couple, however, degraded exponentially once wear was induced and galling proliferated across the contact surfaces. The ALH team continued development of coatings and application processes to obtain an optimum wear couple with static and kinetic friction coefficients as the constraints. The coating development process began with empirical testing to duplicate the wear pattern and hardware degradation that was experienced during ALH testing.

Figure 8 shows a rub rig which simulates one of the radial journal bearings from the ALH. This empirical testing was successful, through iteration, in duplicating all the wear parameters experienced during ALH testing. This includes wear patterns in both the static and rotating parts, vibratory response and a characteristic audible signature that was recorded during both the ALH runs and rub simulation.

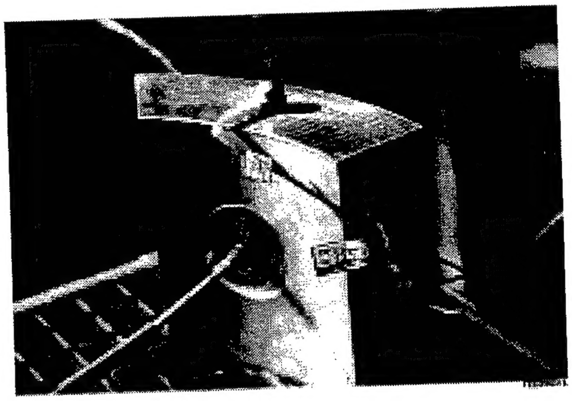


Figure 8 – ALH Rub Rig

A parallel effort involved lab work to evaluate multiple coatings, approximately 27, and combinations of these when applied to a constant substrate material. Figure 9 shows the configuration of the rub rig for testing at cryogenic conditions.

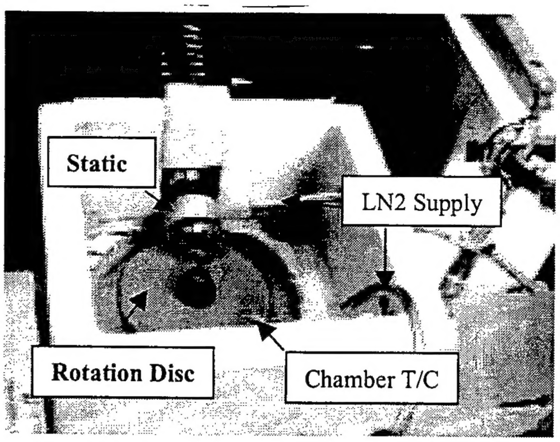


Figure 9 – Cryogenic Tribology Test Rig

The test protocol was as follows: simulate 20 "touchdown cycles", 30 seconds per contact, LN2 temperature. 35 KSI contact stress, 500 in/sec sliding speed and a PV value of ~ 18.3 x 10^6 lbs/in-sec. Additionally, adherence testing (LHe temperatures), indentation testing, CTE and biaxial modulus experiments were performed on each subject. Figures 10, 11 are Scanning Electron Microscope (SEM) images of specimens after indentation testing. Notice the differences around the edge of the crater.

and

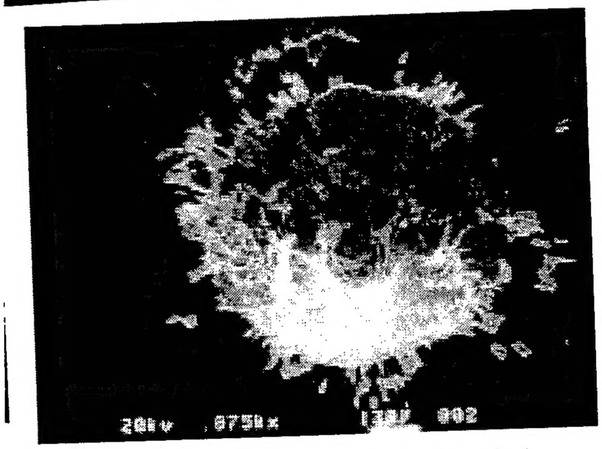


Figure 10: Wear Testing Results, Sample A

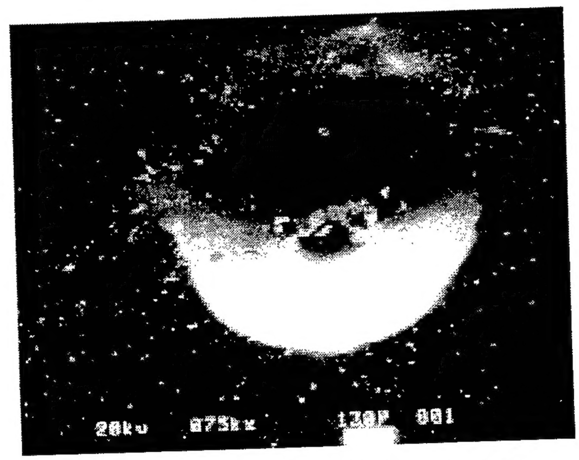


Figure 11: Wear Testing Results, Sample B

Figures 12, 13 are representative of the rub pair frictional data that was recorded during the multiple cycle wear testing.

The benefits of the laboratory testing resulted in changing the original design coating to the current configuration. The results have been dramatic with a step increase in damage tolerance allowing numerous runs without re-coating.

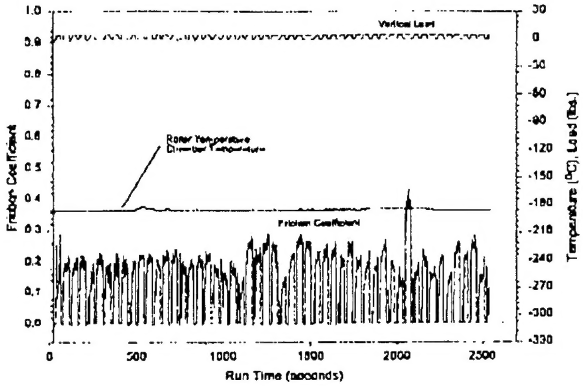


Figure 12 – Sample Rub Pair C Tribological Test Data

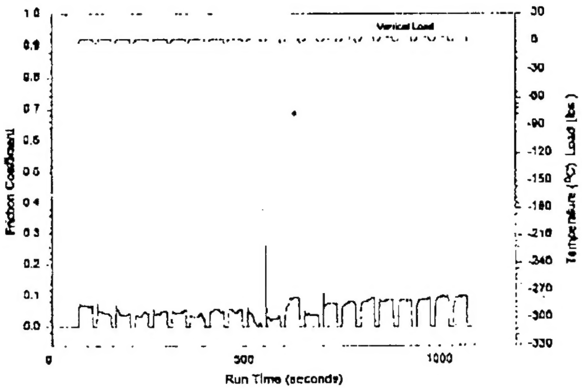


Figure 13 - Sample Rub Pair D Tribological Test Data

ALH Capacitive Proximity Sensors

Capacitive proximity sensors are being used successfully in the ALH turbopump test program. These sensors are highly accurate and not sensitive to the large temperature changes experienced in cryogenic environments. Sensor location and target geometry were optimized to achieve axial, radial and rotor angular speed information.

Principle of Operation:
The sensors' operation is governed by the parallel plate capacitor principle. The capacitance formed between the sensor and target varies as a function of the distance between them and can be expressed by:

$$C = K\left(\frac{A}{D}\right)$$

Where:

- C =Capacitance
- K =Dielectric constant of the medium between the sensor and the target
- D =Distance between sensor and target
- A =Sensor sensing area

One axial proximity sensor is located in the turbine exit area and views a target location on that end of the rotor. This target area is flat which provides for a low noise, high accuracy sensor output signal. The data obtain from this sensor, shown in Figures 3, 4 and 6 provided high quality rotor axial positioning and frequency content information. Two radial sensors are located in the same axial plane but are separated radially 90 degrees apart. This quadrature separation ensures that radial motion in any direction will be detected. The radial target area also incorporates rotational motion features. These features are areas where the target surface makes a step change in gap away from and back towards the sensor tip. They appear as a small blind hole in the surface and as a large pulse on the sensor's output signal. The resulting pulses, three per revolution, can be post processed to determine rotor angular velocity and acceleration. Figure 14 shows the output of a radial probe with the superimposed rotation indications. The plot shows the radial motion diminishing, moving from left to right in time.

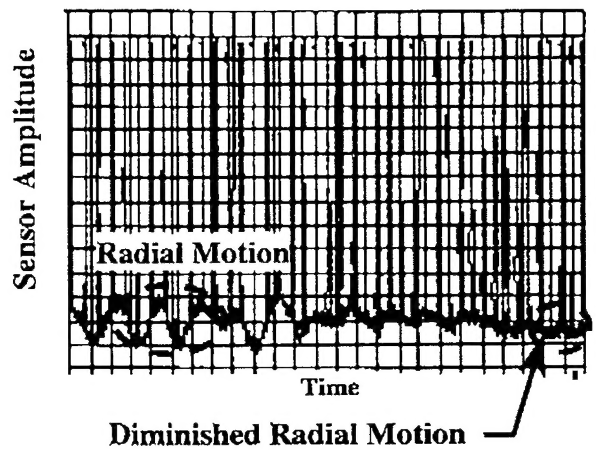


Figure 14 - Radial proximity sensor output showing rotor orbit and rotation indications

Rotor Support System

Fluid film bearing performance evaluation has focused on start transient operation. Utilizing data from the radial proximity sensors as shown in Figure 14, it has been possible to determine the time of radial bearing lift-off. Radial bearing operation has been satisfactorily demonstrated during low power tests. Indications are that under nominal conditions radial bearing performance matches quite well with expectations.

Thrust bearing operation requires further evaluation. An understanding of axial loads has just reached a sufficient level of maturity to support component testing. Successful testing requires matching turbine and pump axial loads to the capability of the thrust bearing, which is highly dependent upon rotor speed.

Adverse influences from the facility have also been identified. Various options to mitigate the impact of facility induced transients are being evaluated. Future ALH testing will focus on defining the capabilities of the thrust bearing at low power to reduce the risk of severe hardware damage during future tests.

SUMMARY

The design of the ALH turbopump has already demonstrated a number of objectives critical to attaining the IHPRPT Phase I Upperstage Demonstrator goals. Early on in the program, the ability to quickly assemble and disassemble the turbopump was realized, validating the original design philosophy and process based on reduced parts count and manufacturing technologies. This was an early indication of assembly/support cost and weight savings. To achieve the final objectives, the ALH has required more testing to demonstrate the increased thrust-to-weight and reduced failure rate goals.

Further testing has allowed a more refined model of both the turbopump performance and the facility characterization. These refinements have helped elucidate the sensitivities of this turbopump design in the areas of rotordynamics, axial load control, turbine torque, and wear tolerance. In all four areas, essential design and manufacturing data has already been collected and integrated back into the design, where appropriate, to ensure future success.

The testing of the ALH turbopump has experienced eight builds. Each build has led to a more thorough understanding of the required final knowledge base required before the pump can be considered ready for an Engineering and Manufacturing Development program. Although difficulties have been encountered, the knowledge base accrued in the critical areas required to understand a fully fluid film supported rotor system in liquid hydrogen has allowed continued success in the test program.

Once component testing of the ALH is completed the turbopump will be integrated into the Upper Stage Demonstrator (USD). USD testing will demonstrate the systems level improvements of the ALH technologies. Future P&W propulsion systems such as the RL200 reusable booster engine and growth versions of the new RL50 upper stage engine will need the technologies derived from the ALH. The RL50 can replace the two RL10 engines of the Atlas increasing reliability and replace the single RL10 engine of the current Delta III and future Delta vehicles improving system performance, thereby supporting the efforts of these launch systems in meeting EELV program goals.

Through intensive engineering efforts to understand the lessons learned and a consistent and methodical approach to testing, the ALH turbopump will demonstrate the key technologies required to support the Upperstage Demonstrator and future advanced expander engines.

References:

Reference 1: Rodriguez, J., Fredmonski, A., Montesdeoca, X., " Design and Test of a Radial Inflow Turbine for an Advance Liquid Hydrogen Turbopump," AIAA-00-0158, 36th AIAA/ ASME/SAE/ ASEE Joint Propulsion Conference, July 2000.

Reference 2: White, F. M., "Fluid Mechanics", McGraw-Hill Book Company, New York, 1986.